Frontiers in Agronomy

TYPE Original Research
PUBLISHED 30 January 2025
DOI 10.3389/fagro.2024.1502786

Check for updates

OPEN ACCESS

EDITED BY
Moritz Von Cossel,
University of Hohenheim, Germany

REVIEWED BY
Gilbert Koskey,
Sant'Anna School of Advanced Studies, Italy
Angelika Kliszcz,
University of Agriculture in Krakow, Poland

*CORRESPONDENCE
Stanley Karanja Ng'ang'a
s.karanja@cgiar.org
Jonathan Mockshell
j.mockshell@cgiar.org

RECEIVED 04 October 2024
ACCEPTED 29 November 2024
PUBLISHED 30 January 2025

CITATION
Ng'ang'a SK, Ogutu SO, Tibebe D, Akinyi D and Mockshell J (2025) Comparative profitability of agroecological practices in Ethiopian wheat farming. *Front. Agron.* 6:1502786. doi: 10.3389/fagro.2024.1502786

Comparative profitability of agroecological practices in Ethiopian wheat farming

Stanley Karanja Ng'ang'a[1]*, Sylvester Ochieng Ogutu[1], Degefie Tibebe[2], Devinia Akinyi[3] and Jonathan Mockshell[4]*

[1]International Center for Tropical Agriculture (CIAT), c/o National Agricultural Research Organization (NARO) Kawanda Agricultural Research Institute, Kampala, Uganda, [2]Performance, Innovation and Strategic Analysis for Impact (PISA4I), International Centre for Tropical Agriculture (CIAT), Kampala, Uganda, [3]Kenya Forestry Research Institute, Nairobi, Kenya, [4]Multifunctional Landscapes & Climate Action Reserach Programs, Alliance Bioversity International & CIAT, Rome, Italy

Introduction: Agroecology is increasingly promoted as a pathway to sustainable food production, aiming to maximize natural resource use while minimizing external inputs with harmful environmental effects. Agroecological practices can enhance farm productivity while ensuring environmental sustainability. However, these practices often require higher initial investments compared to business-as-usual (BAU) practices, and their profitability and relative risks are not well studied. This research evaluates the profitability and risk of adopting agroecological practices among wheat farmers in Ethiopia.

Methods: We conducted a deterministic cost-benefit analysis (CBA) incorporating sensitivity and scenario analysis to evaluate the profitability and relative risks associated with three agroecological practices: certified wheat seed, optimal site-specific inorganic fertilizer application rates, and drainage of waterlogged soils. The analysis considered yield uncertainty, market price fluctuations, and implementation variability to provide robust insights for decision-making.

Results: The deterministic CBA revealed that among the three practices, the use of certified seeds was the most profitable, with a net present value (NPV) of US$ 2,531 ha^{-1}. This was followed by optimal site-specific inorganic fertilizer application, with an NPV of US$ 2,371 ha^{-1}. Drainage of waterlogged soils yielded the lowest profitability, with an NPV of US$ 2,099 ha^{-1}.

Discussion: The results indicate that certified seeds and optimal fertilizer rates offer higher financial returns, making them attractive investments for wheat farmers. However, profitability alone does not guarantee adoption. Other factors, including social and behavioral aspects, influence farmer decisions. Future research should integrate these dimensions to develop comprehensive strategies for promoting agroecological practices.

Conclusion: Adopting agroecological practices has clear economic benefits for Ethiopian wheat farmers, with certified seeds emerging as the most profitable option. These findings provide evidence for stakeholders to design targeted interventions that maximize returns while addressing barriers to adoption.

KEYWORDS
agroecology, innovations, Ethiopia, cost-benefit, wheat, farmers

1 Introduction

Global food systems are at a critical juncture, grappling with unprecedented challenges in providing healthy, accessible diets to all people while safeguarding environmental health (Herrero et al., 2021). These challenges are compounded by hunger, malnutrition, climate change, resource depletion, biodiversity loss, and economic instability, all of which directly threaten farmers livelihoods, and rural development (Fan et al., 2021; Ewert et al., 2023; Mockshell and Kamanda, 2018). Recent crises like the COVID-19 pandemic and the Russia-Ukraine conflict, have further exposed the vulnerabilities within agri-food systems, disrupting supply chains, escalating food prices, and undermining global food security (Ewert et al., 2023; Mockshell and Nielsen Ritter, 2024). Addressing these interlinked issues requires not only innovation in agricultural production but a paradigm shift toward more sustainable, resilient food systems (Piñeiro et al., 2020; Fan et al., 2021).

While much of the literature has underscored the need for such transformations, there remains a notable gap in understanding the financial viability and risk dynamics of transitioning to sustainable practices, particularly for smallholder farmers in sub-Saharan Africa. This study uniquely addresses this gap by focusing on the cost-benefit and risk analysis of specific agroecological practices within the wheat value chain in Ethiopia—a region that is underexplored in this context. Agroecology, recognized as a promising framework for achieving sustainable food systems, incorporates ecological principles to optimize interactions between farming components (Jones et al., 2022). This is because it aim to maximize the use of natural resources and minimize the reliance on external inputs, promoting long-term productivity and environmental sustainability (Wezel et al., 2020). Examples of agroecological practices include using certified local seed (which can be open-pollinated-varieties that promote biodiversity), applying fertilizers at optimal rates, improving drainage in water-logged soils, rotating crops, and embracing crop and farm diversity, planting cover crops, no-till systems, integrated pest management, and agroforestry practices (Piñeiro et al., 2020). However, there is limited empirical evidence on the profitability and relative risks of such practices, especially under smallholder farming conditions, where resource constraints and market access challenges further complicate decision-making.

In this paper, we take a novel approach by conducting a detailed cost-benefit analysis (CBA) coupled with sensitivity analysis to evaluate three specific agroecological practices prioritized by Ethiopian wheat value chain stakeholders: certified seeds, optimal site-specific fertilizer application, and waterlogged soil drainage. Contrary to business as usual (BAU) scenarios where farmers often engage in their day-to-day farming practices e.g., without using certified seeds, optimal site-specific inorganic fertilizer application rate, and draining waterlogged soils, the use of such agroecological practices could improve soil drainage, soil nutrient availability, agricultural productivity, and profits (Ali et al., 2015; Ayalew et al., 2022; Pais et al., 2023). These agroecological practices can, therefore, play a critical role in protecting the ecosystem by ensuring more efficient use of natural resources and strengthening the capacity to adapt to climate change, resilience and environmental sustainability (Negra et al., 2020; Jones et al., 2022). However, the uptake of agroecological practices among smallholders in sub-Saharan Africa is still very limited, constrained by factors such as high initial investment costs, limited access to technology and information, labor demands, market access and potential trade-offs between maximizing productivity in the short term and achieving long-term sustainability and environmental protection (Akinyi et al., 2022; Mockshell and Kamanda, 2018). Additionally, some practices often associated with agroecology, such as the use of certified seeds and optimal fertilizer application, can be complex and require specific knowledge, which can further limit adoption by smallholder farmers.

Despite efforts to promote the adoption of agroecological and other sustainable agricultural practices, existing literature and climate adaptation programs have rarely examined the profitability and relative risk surrounding the practices (Akinyi et al., 2022; Mogaka et al., 2022). To help address this research gap, we evaluate the profitability (costs and benefits) and the relative risk through sensitivity analysis associated with three agroecological practices (certified seed, optimal site-specific inorganic fertilizer application rate, and drainage of waterlogged soils) among smallholder wheat farmers in Ethiopia. Sensitivity analysis, in particular, is a key innovative aspect of this study. It allows us to systematically assess how variation in critical parameters-such as input costs, crop yields, and climatic conditions—affect the profitability and risk of adopting these agroecological practices. This approach not only enhances robustness of our finding but also provides nuanced insights into how these practices might perform under different scenarios, which is crucial for smallholder farmers facing a range of uncertainties.

Unlike many existing studies that focus broadly on sustainability or productivity, our work delves into financial and risks-related dimensions of adopting these practices, providing crucial insights for smallholder farmers, policymakers and investors. By incorporating sensitivity analysis, we address a significant gap in the literature, offering a more dynamic understanding of how these practices might impact farm-level economics and risks profiles in varying conditions.

We conduct this study in Ethiopia because Ethiopia, like most other countries in sub-Saharan Africa, is affected by hunger and malnutrition, loss of biodiversity, conflicts, and climate change-related problems (FAO et al., 2022). Efforts to increase crop production in Ethiopia have recognized the importance of agroecology and implementing programs (e.g., the national soil and water conservation program, the sustainable land management program) and practices (e.g., conservation tillage, drought-tolerant varieties, and site-specific wheat varieties) that aim at ensuring sustainable production (Schmidt and Tadesse, 2019; Tanto and Laekemariam, 2019; Desta et al., 2021; Belete et al., 2022). Ethiopia, also, present a particularly compelling case for this analysis due to its critical role in wheat production within Africa, coupled with its ongoing struggle against food insecurity, climate-related stressors and soil degradation (FAO et al., 2022; Nigus et al., 2022). As the second-largest producer of wheat in the continent, Ethiopia's ability to sustain and enhance wheat production has significant implication for both national and regional food security. Despite this, wheat farmers in Ethiopia face systemic challenges, including limited access to improved seed varieties and degrading soils, which agroecological practices could help to mitigate (Anteneh and Asrat, 2020; Desta et al., 2021). By focusing on wheat, this study not only addresses a critical agricultural sector but also contributes to a broader understanding of how agro-ecological principles can be scaled in context that are vital to food security.

The remainder of this paper is structured as follows: Section 2, details the study area, data collection methodology, and CBA framework. Section 3 presents the results of our analysis, followed by a discussion of key findings, policy implications, and conclusions in Section 4.

2 Materials and methods

2.1 Study sites

The study area comprises three districts in Ethiopia: Goba, Lemo, and Munesa. Goba district is in Bale zone, Oromia Regional State of Ethiopia. It lies between 5°57'30"N to 7˚12'00"N latitude and 39°35'00"E to 40°15'00"E longitude (Assefa et al., 2024). Its altitude ranges from 2400 to 4377 meters above sea level (masl). It has a total area of 1,674 km^2, and is located 445 km away from Addis Ababa, the capital city of Ethiopia (Legesse et al., 2019). Its monthly temperature ranges from 4°C to 25°C, and annual rainfall varies from 900 mm in the lowlands to 1,400 mm in highlands (Assefa et al., 2024). Agriculture is the most dominant economic activity in the district, with cereals (including wheat), horse beans, field beans and lentils being the most important crops grown (Legesse et al., 2019).

Lemo district is one of the districts in the Hadiya zone of southern Ethiopia. It lies between 7° 24′ 0′′N and 7° 44′ 30′′N latitude and 37° 44′ 0′′E and 38° 3′ 0′′E longitude (Sedebo et al., 2021). Its altitude ranges from 1500 to 2500 masl (Tadesse et al., 2014). It has a total area of 34,986 ha (Sedebo et al., 2021), and is located about 230 km southwest of Addis Ababa (Addise et al., 2022). Its mean annual temperature ranges from 15 to 22°C and rainfall ranges from 700 to 1,260 mm (Sedebo et al., 2021). Cereals are the most cultivated crops in the area, accounting for about 60% of all crop production. Wheat is the most dominant cash crop produced in the district (Sedebo et al., 2021).

Munesa district is located in the East Arsi zone of Oromia region, Ethiopia. The district lies between latitudes 7°12′ to 45° N and longitude 52° to 39°03'E in central Ethiopia (Adunea and Fekadu, 2019). Munesa is located 232 km southwest of Addis Ababa. Its altitude ranges from 2080 to 3700 masl and is characterized by mid sub-tropical temperature ranging from 5 to 20°C. The total land area covered by the district is 1031 km^2 with a total population of 211,762 (Adunea and Fekadu, 2019). Crop-livestock integration is the dominant farming system within the district. Major cereal crops cultivated include wheat, barley, and maize (Adunea and Fekadu, 2019).

2.2 Prioritization of agroecological innovations/practices

The CCAFS-CSA Prioritization framework (FAO, 2010; Corner-Dolloff, 2014) was adopted and customized to identify and prioritize agroecology practices in this study. This framework guides stakeholders through the process to filter a long list of applicable agroecology practices into prioritized ones (Khatri-Chhetri et al., 2017; Thornton et al., 2017). According to Corner-Dolloff (2014), the approach involves three major phases:

i. Compilation and assessment: Collecting a long list of agroecology practices and assess/characterize them based on FAO's 10 elements of agroecology indicators.
ii. Prioritization: Identifying and shortlisting top agroecology practices based on scores.
iii. Cost-benefit analysis: Conducting cost-benefit analysis of the selected agroecology practices.

The identification and prioritization for wheat value chain were conducted during a workshop by involving 20 participants. These participants included district-level agricultural experts and cooperative representatives from Munesa and Goba districts of Oromia region, and Lemo district of central south region of Ethiopia, agricultural researchers from Ethiopian Institute of Agricultural Research, federal experts from Ministry of Agriculture, agroecology practitioners from NGOs and Civic society, and researchers from Haramaya University and Alliance of Bioversity International CIAT. Participants were divided into three groups representing the three districts considered in this analysis. The workshop employed the customized CCAFS CSA prioritization framework (Lizarazo et al., 2021; Mwongera et al., 2018) using the following steps:

1. Identification: Participants identified 13 agroecology practices implemented in wheat production system in Ethiopia based on their knowledge and literature. The practices identified were certified wheat seeds, site specific optimal fertilizer, drainage-BBF with wheat, crop rotation with leguminous and oil crops, agroclimate advisory, integrated pest management, crop residues, organic amendment-compost, agroforestry, green manuring during off season, fallow, optimal irrigation and farmyard manure.
2. Evaluation: The FAO's 10 agroecology elements (diversity, co-creation and sharing of knowledge, synergies, efficiency, recycling, resilience, human and social values, culture and food traditions, responsible governance, circular and solidarity economy) were used as indicators to evaluate the practices.
3. Scoring: Participants scored the 13 agroecology practices against the 10 agroecology elements using Likert scale from −3 to 3: high positive effect, 2: medium positive effect,1: low

positive effect, 0: no effect, −1: low negative effect, −2: medium negative effect, −3: high negative effect). Scoring was done through discussion and consensus.

4. Aggregation: The Likert score for each agroecology practice against the 10 elements were summed up and averaged.
5. Ranking: Practices were ranked based on the average scores. Results from each group were presented in a plenary for further discussion, review, cross-fertilization, and experience sharing among the group.
6. Discussion: The top three agroecology practices were described in detail.

2.3 Agroecological intervention

The purpose of this study is to estimate the net benefit of three prioritized agroecological innovations and to estimate the net impact of these innovations on the income. There is thus a need to first understand the revenues and expenditures of the activities adopted by the households in relation to these innovations. Next, one needs to compare the values with revenues and expenditures under the studied innovations. This comparison will allow one to evaluate whether the incremental benefit of innovations is worth the cost. This is carried out by building both a "with" and "without" scenario with respect to revenues and expenditures profiles. An incremental cash flows statement is then constructed for the entire evaluation period of thirty years.

2.3.1 "Without" intervention/"Business as Usual" scenario

2.3.1.1 Certified seed

In the absence of certified seeds, wheat farmers rely on traditional or uncertified seeds that often have lower germination rates and genetic purity. This results in inconsistent yields, higher susceptibility to pests and diseases, and reduced resilience to environmental stresses (Baglan et al., 2020). The overall productivity is lower, leading to less marketable produce and reduced income for farmers. Soil health may also deteriorate over time as lower-quality seeds do not support robust plant growth (Rios et al., 2009).

2.3.1.2 Drainage systems

Without proper drainage systems, waterlogging can become a significant issue, especially during heavy rainfall. This can lead to root rot, reduced plant growth, and lower wheat yields (Iizumi et al., 2024). Poor drainage also exacerbates soil erosion and nutrient leaching, leading to long-term soil degradation (Motarjemi et al., 2023). The economic impact includes lower yields and quality, resulting in reduced market prices and income for farmers (Rios et al., 2009).

2.3.1.3 Without optimal fertilizer rates

Using non-optimal fertilizer rates—either too much or too little—can lead to several problems. Over-fertilization can cause nutrient runoff, pollution, and soil acidification, while under-fertilization results in poor plant growth and lower yields (Caplan et al., 2017). Inefficient fertilizer use leads to wasted resources and additional costs without corresponding increases in productivity (Smil, 2004). This negatively impacts both the environment and farmer incomes due to reduced yield and quality.

2.3.2 "With" intervention scenario

2.3.2.1 Certified seed

Using certified seeds ensures high germination rates, genetic purity, and improved resistance to pests and diseases. This results in more consistent and higher yields, better-quality produce, and increased farmer income (Dhiman et al., 2010). Certified seeds also contribute to better soil health as they are often bred to be more efficient in nutrient uptake, reducing the need for excessive fertilizer application. The initial investment in certified seeds is offset by the increased productivity and market value of the crops.

2.3.2.2 Drainage systems

Implementing effective drainage systems helps prevent waterlogging, promoting healthier root systems and optimal plant growth (Iizumi et al., 2024). This leads to increased wheat yields and better-quality produce. Proper drainage also minimizes soil erosion and nutrient leaching, contributing to long-term soil fertility and sustainability (Harris et al., 2016). The initial costs of installing drainage systems are justified by the increased productivity and resilience of the agricultural land, ultimately enhancing farmer incomes and market competitiveness.

2.3.2.3 Optimal fertilizer rates

Applying optimal site-specific inorganic fertilizer rates ensures that plants receive the necessary nutrients for optimal growth, resulting in higher yields and better-quality wheat (Mesfin et al., 2021). This practice improves nutrient use efficiency, reducing the risk of environmental pollution from runoff and maintaining soil health (Wang et al., 2023). Farmers benefit economically from higher productivity and lower costs associated with overuse or underuse of fertilizers. The environmental impact is also positive, as optimized fertilizer use contributes to sustainable farming practices.

2.4 Data collection

The study used primary data collected in 2023 from key informants in three districts: Goba, Lemo, and Munesa. The key informants included stakeholders from the ministry of agriculture, universities, research institutes, farmer group representatives, and farmers. Key informants were purposively selected based on their experience with both "Business as Usual" (BAU) or "Without Intervention Scenario" and "With Intervention (i.e., agroecological practices, specifically "optimal site-specific inorganic fertilizer rate", "certified seeds" and drainage in the wheat value chain) Scenario. Data collection was done using structured household questionnaires, which included qualitative variables (e.g., variables identifying and describing the agroecological practices adopted and the BAU case, variables describing reasons why agroecological practices are preferred) and quantitative variables (e.g., on yield, prices of inputs and output, labor, and services costs). The questionnaire used to collect the data is provided in the Appendix. Literature review was conducted to fill any potential data gaps, such as historical variations in yield, input prices, and discount rates. Sixteen key informant interviews were conducted. Eight of the interviews compared application of fertilizers at optimal rates with BAU practices. Six interviews compared the use of certified wheat seed with BAU practices, while two other interviews compared draining of water-logged soils with BAU practices.

2.5 Data

Two types of surveys were conducted for this study. The first survey aimed at collecting data about the innovations from the Key Informants. The data included details of the most common agroecological practices applied by wheat farmers in the study area. About 13 agroecological practices were identified by the key informants as the most widely practiced. A second survey focused on cost-benefit analysis (CBA) of the three innovations that were innovations. This survey captured cost data across three categories: implementation (machinery, equipment, labor, infrastructure), maintenance (lifespan), and activity (ongoing operational expenses). Refer to Ng'ang'a et al. (2021) for a detailed breakdown of these cost categories, and to Appendix A for the specific questions that were asked.

A before-and-after costing approach was used for data collection. Experts compared the innovation's installation, maintenance costs, and resulting yields to a baseline business-as-usual (BAU) scenario and the innovation (also referred to as agroecological practices). The experts provided detailed information on factors impacted by the innovation: installation, maintenance, operation costs; input demand (seeds, fertilizers); yield changes; and cost of capital. This involved itemizing all activities associated with the implementation (establishment), maintenance, and operations (post-harvesting activities) of the BAU and the innovations variable inputs, transportation costs, yield per hectare, and market prices for both BAU and the innovation. All data was then converted into monetary values.

Costs were categorized into production costs (labor for various tasks, equipment, services, variable inputs, transportation) and benefits (gains from the innovation, e.g., increased yield, reduced maintenance etc.).

The study utilized both primary and secondary data sources. Primary data came from the expert survey. Secondary data, primarily from peer-reviewed literature and country reports, filled any gaps in the primary data, such as historical variations in yield, input prices, and discount rates.

2.6 Analysis

Following value chain selection and innovation prioritization (Section 2.2), an economic analysis assessed implementation costs. A Microsoft Excel-based CBA template was employed to capture all relevant costs, including initial investments, ongoing implementation, maintenance, and operation for both the BAU scenario and the proposed innovations. Notably, most innovations incurred upfront costs, followed by operation and maintenance expenses. Benefits, however, were primarily realized after the first year of implementation. Future benefits were discounted at a rate reflecting respective country government interest rates, as provided by expert surveys.

For most innovations, the primary benefits stemmed from reduced production costs and improved yields due to enhanced input use precision. Unlike ex-post CBA, which relies on historical data, ex-ante CBA inherently involves uncertainties (Farrow and von Winterfeldt, 2020). However, in many cases, the anticipated relative yield improvement (coupled with reductions in installation, maintenance, and operational costs) often provides sufficient grounds for estimating benefits associated with specific innovation implementation. Future maintenance and operational costs were considered based on the assumption of performance similar to existing, comparable innovations.

Cost-benefit analysis (CBA) aggregates the present value of all benefits and costs, both private and public, to assess the economic viability of investments. Private benefits and costs accrue directly to those involved in producing and consuming the innovation's associated products. In this study, a farmer-centric ex-ante CBA model was employed to evaluate the profitability of innovations from the perspective of the implementer. This approach focuses on private benefits (e.g., reduced production costs, increased yields) and private costs (e.g., implementation, maintenance) borne by the farmer. Public benefits and costs, also known as externalities (e.g., environmental impacts), are not considered here. Recognizing the time-varying nature of costs and benefits, the analysis incorporates discounting using country-specific prevailing discount rates to account for the time value of money.

2.7 Analytical model and profitability indicators

The benefit associated with innovation is computed as the difference between the net benefits associated with implementing the innovation and the net benefits of conventional or normal farming without any form of improvement also referred to as BAU (Equation 1).

$$\text{Innovation Net Benefits}_{jt} = \frac{\left[\sum_{i=1}^{n}(\text{Innovation Net Benefit}_{jt} - \text{BAU Net Benefits}_{jt})\right]}{n} \quad (1)$$

Where t stands for the time (in years) that the farmers invest in the innovation j and n is the total number of experts interviewed per specific innovation and its associated BAU. The unit of analysis is standardized to per hectare basis.

This study employs three key profitability indicators: net present value (NPV), internal rate of return (IRR), and payback period (PP). NPV represents the discounted sum of the incremental net benefits generated by the innovations compared to the BAU scenario over the innovation lifecycle within a specific value chain for each country. A positive NPV and an IRR exceeding the discount rate are generally considered favorable investment indicators. Equation 2 details the NPV calculation.

$$NPV_t^{Innovation} = \left[\sum_{t=1}^{T} \frac{1}{(1+r)^t} \left(\sum_{i=1}^{n} \left[P_{nt} \times \Delta Y_{nt}^{Innovation-BAU} - \Delta C_{nt}^{Innovation-BAU} \right] \right) \right] \quad (2)$$

Where T stands for the number of years considered for the NPV calculation, r stands for the discount rate used to calculate the present values of future cash flows, t stands for the time (in years) that the farmers invest in the innovation and n is the total number of key experts interviewed about innovation at a given time, and P stands for price. ΔY and ΔC stands annual change in yield for output and annual change in costs respectively due to the innovation compared to the BAU, respectively.

The discount rate employed reflects the time value of money for farmers, considering the market rate of return on their investments (Howarth, 2009). The IRR, calculated using Equation 3, represents the discount rate at which the NPV of the innovation equals zero (Hartman and Schafrick, 2004). In simpler terms, it is the maximum acceptable borrowing rate for an investment that allows full recovery of costs (installation, maintenance, operation) and achievement of a break-even point (Noori et al., 2018). Innovations with an IRR exceeding the discount rate are generally considered financially viable investments.

$$NPV = \sum_{t=1}^{n} \left[\frac{B_t - C_t}{(1+r)^t} \right] = 0 \; IRR > 0 \quad (3)$$

Where Bt stands for the accrued benefits at time t, Ct stands for the investment and recurrent costs incurred for innovation at time t, t stands for the period or lifetime of the innovation, and r is the interest rate or discount rate. The payback period (PP) represents the time horizon required for an investment to recover its initial capital outlay. In simpler terms, it reflects the duration needed to recoup the funds invested in installing and maintaining the innovation (Equation 4). PP serves as a simplified metric for assessing the liquidity of an investment, indicating how quickly the investor can regain their initial investment.

$$Payback \quad Period \quad (PP) = \left[\frac{Investment \quad Cost}{Net \quad annual \quad Cash \quad Inflows} \right] \quad (4)$$

2.8 Values used in computing the profitability indicators

To model the physical response curves for activities affected by the innovation, it was assumed that the yields for the products affected by the innovations followed a response function characterized by a lag period, then start increasing and continues to reach maximum and following which a linear plateau is experienced. The assumption that yields follow a response function characterized by an initial lag period, subsequent increase, and eventual plateau is justified based on several well-documented agricultural phenomena. Firstly, innovations in agricultural practices often require an adaptation period where farmers and systems adjust to new methods, resulting in an initial lag. As the innovation is fully adopted and optimized, yields typically experience a significant increase due to improved efficiencies, better resource utilization, and enhanced crop management practices. Finally, the plateau phase reflects the natural limitations of the innovation, where maximum potential yields are reached, and further increases become minimal, aligning with the diminishing returns principle in agricultural production. This model mirrors empirical evidence observed in numerous agricultural studies, ensuring a realistic and credible representation of yield dynamics over time (see Ng'ang'a et al., 2021 for more details).

2.9 Sensitivity analysis

Uncertainty surrounding key cost and benefit parameters can significantly influence the decision related to economic viability of innovations. To assess the robustness of our findings, this study employed a sensitivity analysis The initial step involved break-even analysis, which identifies the critical change required in cost or benefit parameters for the Net Present Value (NPV) to reach zero or the initial investment amount for each innovation.

Next, a tornado analysis (SenseIt, 2017) was conducted to visualize the impact of parameter uncertainty on NPV. This analysis began by establishing a baseline scenario with best estimates for all parameters. Subsequently, lower and upper bounds were defined for each uncertain parameter to capture a realistic range of uncertainty. Finally, the NPV was calculated under scenarios where each parameter took on its lowest and highest values, allowing for a visual assessment of the most influential parameters.

Following the tornado analysis, a Monte Carlo simulation using @Risk software (Palisade Corporation, 2013) was performed for a more comprehensive uncertainty analysis. Triangular probability distributions were assigned to each uncertain parameter. Triangular distributions were chosen for their computational efficiency and because they can effectively capture potential tail uncertainties, even though they might exaggerate them to some extent (Thrift and von Winterfeldt, 2021). The base case value served as the most likely value, while lower and upper bounds were selected to encompass a realistic range of uncertainty. By randomly sampling from these parameter distributions, thousands of possible NPV outcomes were simulated (n=10000 simulations), generating a distribution of potential net benefits for each innovation.

The results are summarized using the 5th percentile, median, and 95th percentile of the simulated NPV distribution. This approach provides a comprehensive picture of the potential range of net benefits for each innovation, considering the inherent uncertainties in the underlying parameters.

3 Results

This study investigated the impact of three agricultural innovations on crop yield in Lemo, Munesa, and Goba districts. The innovations evaluated were optimal site-specific inorganic fertilizer rate, certified seed, and drainage improvements. Data was collected for a period of 30 years, with yield responses measured from year 1 to year 2 after implementation.

3.1 Yield changes

Table 1 summarizes the average yield per hectare for the BAU, the innovation lifecycle, the time when innovation started to have a physical impact on wheat and when it reached maximum, the innovation lifecycle, the average change in yield per hectare following the implementation of the innovation were estimated from the data collected from the experts. All three innovations resulted in significant yield increases compared to BAU practices. The average yield increase for the optimal fertilizer rate was 677 kg/ha (or 22%), the highest among the three innovations. Certified seeds demonstrated a consistent yield improvement of 603 kg/ha (or 18%), while drainage improvements provided an average yield increase of 617 kg/ha (or 20%).

The data also revealed variability in yield response across districts and practices. The optimal fertilizer rate exhibited the highest variability in both BAU and innovation scenarios, suggesting potential benefits from further tailoring fertilizer application based on local conditions. Certified seeds and drainage improvements showed relatively lower variability, indicating a more consistent response across districts. However, all three innovations result in a positive increase in yield per hectare, demonstrating their effectiveness in improving agricultural productivity. These yield increases (of 18–22%) translate to significant economic benefits for farmers. Increased crop production can lead to higher income, improved food security, and potentially lower food prices for consumers.

3.2 Implementation and maintenance costs

The economic feasibility of each innovation extends beyond yield increases and requires consideration of implementation and ongoing maintenance costs. The results in Table 2 reveal a range of costs associated with each innovation. The implementation costs for the optimal fertilizer rate is approximately US$298.60 per hectare across Lemo, Munesa, and Goba, with an estimated standard deviation of US$74.09. Year-one maintenance costs an average of US$235.00 per hectare. In Munesa and Goba, certified seed implementation averages US$235.30 per hectare, with a standard deviation of US$58.83. However, year-one maintenance costs for certified seeds are higher at US$331.00 per hectare. Drainage improvements, implemented only in Munesa, have a higher average implementation cost of US $302.40 per hectare with a standard deviation of US$75.60. Year-one maintenance costs for drainage are US$243.90 per hectare. The high maintenance costs can be attributed to several factors. Firstly, the region's specific geographic and hydrological conditions may require more extensive and frequent maintenance efforts to ensure effective drainage. Studies have shown that areas with higher rainfall variability and poor soil drainage capacity necessitate significant and ongoing investments in drainage infrastructure to prevent waterlogging and maintain soil health (Awulachew, 2006).

3.3 Financial returns

The results reveal that all three agroecological innovations yield positive NPVs, indicating strong long-term profitability for farmers (Table 3). Among them, certified seed option emerges as the most lucrative, with the highest NPV of US$2,531, followed closely by the optimal fertilizer rate at US$2,371, and drainage at US$2,099. In addition, given the prevailing market discount rate of 10%, both the certified seed and optimal fertilizer rate demonstrate remarkably high IRRs each exceeding 100%. The drainage option also performs well, with an IRR of 106%. Notably the payback period for all three innovations is just one year, underscoring their capacity to quickly recover the initial investment.

These results, characterized by high NPVs and IRRs far above the market discount rate, suggest that each of these innovations presents a financially attractive opportunity. Investing in any of the three would likely lead to substantial financial gains. However, the certified seed option stands out as the most financially appealing, given its superior NPV and IRR, making it the best investment choice in terms of potential returns.

TABLE 1 Average yield impact of agricultural innovations in Ethiopia.

Districts covered	Innovation Name	Evaluation period (Years)	Response start (Year)	Response reach maximum (Years)	Average yield BAU (kg/ha)	Average yield (Innovation) (kg/ha)	Average increase (Kg/ha)
Lemo, Munesa, Goba	Optimal site-specific inorganic fertilizer rate*	30	1	2	3045 ± 979	3722 ± 1204	677
Munesa, Goba	Certified seed*	30	1	2	3344 ± 909	3947 ± 1060	603
Munesa	Drainage**	30	1	2	3033 ± 776	3650 ± 900	617

**, *, stand for n = 2 and n = 6 respectively; evaluation period is synonymous with innovation lifecycle.

TABLE 2 The cost of implementation and maintenance and operation of each innovation.

Districts covered	Innovation Name	Implementation (US$/ha)	Maintenance and operation (US$/ha/Year)
Lemo, Munesa, Goba	Optimal site-specific inorganic fertilizer rate*	298.6 ± 74.09	235 ± 21.36
Munesa, Goba	Certified seed*	235.3 ± 7.56	331 ± 22.50
Munesa	Drainage**	302.4 ± 74.09	243.9 ± 14.02

**, *, stand for n = 2 and n = 6 respectively.

Supplementary Tables A1–A3 provide detailed cash flow statements in real values for the total investments in "Optimal site-specific inorganic fertilizer rate," "Certified seed," and drainage innovations, respectively. These tables further illustrate the financial differences between the "with" and "without" scenarios for each innovation.

3.4 Sensitivity results

3.4.1 "Optimal site-specific inorganic fertilizer rate" innovation

The sensitivity analysis for the "optimal site-specific inorganic fertilizer rate" innovation (Figure 1) offer a novel probabilistic insight into its financial viability highlighting the renage and likelihood of potential outcomes. Using 10,000 Monte Carlo simulations, the analysis predict with 90% certainty that the NPV will range between $1,117 and $4,341, providing wheat farmers with a nuanced understanding of the financial risks and rewards. The mean NPV of $2,597 reinforces the positive expected value, signaling a promising return on investment.

What sets this analysis apart is its ability to account for uncertainty, a key factor often overlooked in traditional evaluations of agricultural innovations. By integrating probabilistic methods, the study moves beyond static evaluations, offering farmers and stakeholders a clearer, data-driven picture of potential financial outcomes. Notably, the analysis reveals a very low probability of negative returns, further strengthening the case for adopting this innovation under varying market and environmental conditions.

The profitability of the "optimal site-specific inorganic fertilizer rate" innovation is influenced by several key factors. Sensitivity analysis (Figures 2, 3) indicates that annual changes in wheat yield have the greatest impact on NPV, accounting for 66% of the variation. Additionally, the market price per kilogram of wheat and the discount rate play significant roles, contributing 12% and 10% to NPV variation, respectively, while total operation costs account for 8%. These results highlight the need to consider not only direct input costs, such as labor, but also external factors like market fluctuations and long-term financial planning. Understanding how these variables interact is essential for evaluating the potential benefits for wheat farmers in Ethiopia.

TABLE 3 The change in NPV associated with the innovations at the prevailing discount rates.

Innovation Name	NPV (US$)	IRR	Payback period
Optimal site-specific inorganic fertilizer rate*	2,371	106%	1
Certified seed*	2,531	117%	1
Drainage**	2,099	106%	1

**, *, stand for n = 2 and n = 6 respectively, Market discount rate.

3.4.2 "Certified seeds" innovation

The sensitivity analysis results (Figure 4) provides a probabilistic view of the potential net present values (NPVs) for the "certified seeds" innovation. The analysis indicates a 90% probability that the NPV will range between $557 and $3,412, based on 10,000 simulations. With a mean NPV of $1,870, the innovation shows a strong positive expected value. Overall, these results are highly encouraging for wheat farmers, as they suggest a very low risk of negative return from this investment.

The profitability of the "Certified seeds" innovation is influenced by several key factors. The analysis (Figures 5, 6) shows that annual changes in wheat yield have the most significant impact, accounting for 59% of the variation in NPV. Additionally, the market price per kilogram of wheat and labor costs play important role, contributing 17% and 11% to NPV variation, respectively. The prevailing discount rate, which account for the time value of money, influences NPV by 6%. These findings highlights the need to consider not only direct input costs, such as labor, but also external factors like market fluctuations when evaluating the potential benefits of this innovation's potential benefits for wheat farmers in Ethiopia.

4 Discussion

This study investigated the economic viability of three agroecological innovations (optimal fertilizer rate, certified seed, drainage) for farmers in Lemo, Munesa, and Goba districts. The findings hold significant implications for promoting inclusive growth in the rural communities of Ethiopia.

All three innovations: optimal fertilizer rate, certified seed, and drainage, demonstrated substantial yield increases compared to traditional practices. Increased production can contribute to improved food security at the household level and potentially contribute to lower food prices for consumers. This aligns with the concept of inclusive growth, which emphasizes not just

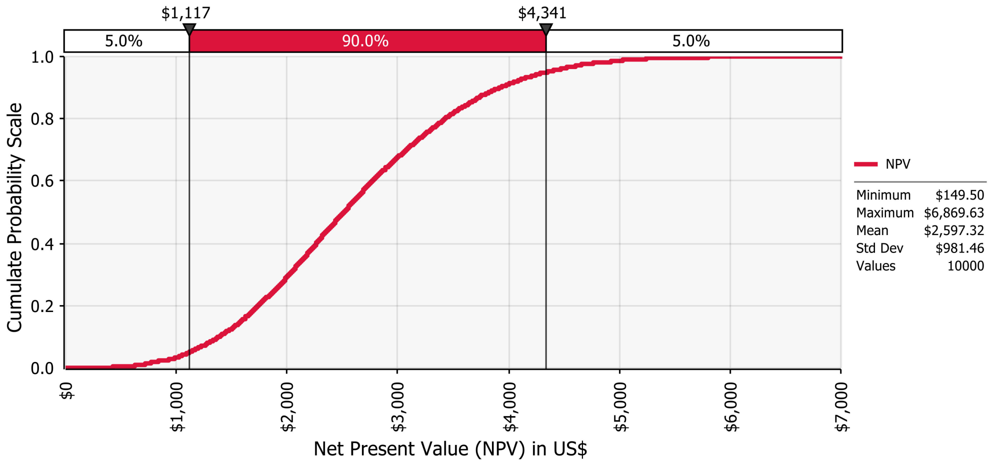

FIGURE 1
The cumulative probability distribution of Net Present Value (US$/ha) for "Optimal site-specific inorganic fertilizer rate" innovation in Ethiopia.

economic prosperity but also equitable distribution of benefits. The finding that certified seeds can increase wheat yields in Ethiopia by 18% is significant compared to the results observed in other countries. Such as Pakistan (15% yield increase), India (10% yield increase), the United States (5% yield increase), and Australia (8% yield increase) (citations), Ethiopia's potential for yield improvement through certified seeds appears considerably higher. This suggests that Ethiopian wheat varieties may be particularly responsive to the genetic improvements found in certified local seeds. Several factors could explain this higher potential. Ethiopia's traditional wheat varieties might be particularly susceptible to diseases or pests that certified seeds offer resistance to (citations). Additionally, the climate and soil conditions in Ethiopia might be more conducive to the improved performance of certified varieties.

A 22% yield increase due to optimal fertilizer rate intervention translates to a significant boost in wheat production. This can have positive economic implications for Ethiopian farmers, leading to increased incomes and improved livelihoods. Furthermore, it can contribute to national food security by increasing domestic wheat production and potentially reducing dependence on imports (Anteneh and Asrat, 2020).

The projected rise in agricultural output due to these innovations has the potential to create a ripple effect through the Ethiopian rural economy. Increased yields can translate to a demand for more labor across various parts of the agricultural value chain. This could include tasks like planting, weeding, harvesting, and post-harvest processing Wider adoption of these innovations could contribute to addressing this need by generating additional employment opportunities, potentially improving livelihoods and reducing rural-urban migration (Jayne and Sanchez, 2021).

Furthermore, ensuring equitable access to these innovations can be instrumental in empowering women farmers who play a crucial role in Ethiopian agriculture. Research suggests that women often face challenges in accessing resources and training opportunities (Williams et al., 2022). By facilitating women's participation in trainings on these innovations and ensuring their access to credit and resources, policymakers can create a more inclusive environment. This can lead to increased agricultural productivity

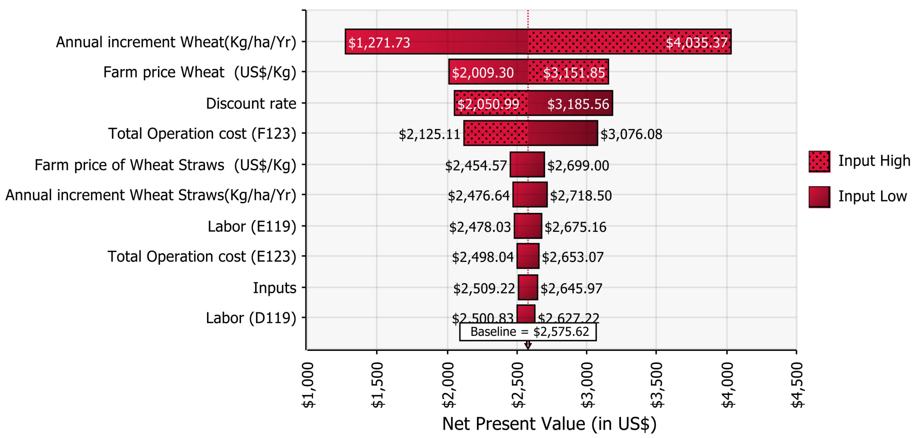

FIGURE 2
Inputs ranked by effect on the mean Net Present Value for "Optimal site-specific inorganic fertilizer rate" innovation in Ethiopia.

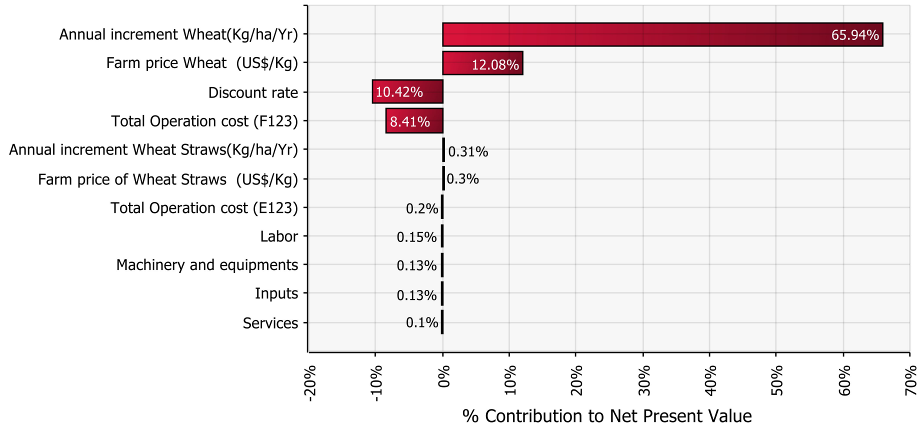

FIGURE 3
Percentage contribution to variation in Net Present Value for "Optimal site-specific inorganic fertilizer rate" innovation in Ethiopia.

managed by women, contributing to household income and overall well-being within communities. Increased agricultural productivity has been shown to have positive correlation with and rural poverty reduction (World Bank, 2009).

The study employed economic measures (NPV, IRR, payback period) to assess the long-term profitability of each innovation. Notably, all three options emerged as financially attractive, with certified seed demonstrating the highest NPV and IRR. The IRR for both certified seed and optimal fertilizer rate exceeded 100%, significantly higher than the prevailing discount rate of 10%. This suggests that these innovations offer a very high potential return on investment, exceeding the opportunity cost of capital. In simpler terms, the return on investment for these practices is projected to be much higher than the interest rate farmers might pay to borrow money to implement them.

While this study highlights the high potential return on investment (IRR) for certified seeds in Ethiopia, it contrasts with findings elsewhere (where)? that show negative returns for wheat production (citations). This discrepancy could be due to several factors. The positive IRR in our study suggests that certified seeds can significantly increase yields and profitability (Elias et al., 2017). Conversely, the negative ROI could be attributed to the use of low-quality improved seeds and wheat leaf rust, factors that can be mitigated through access to high-quality certified seeds and proper disease management practices.

This study underscores the economic viability of all three innovations (optimal fertilizer rate, certified seed, drainage) not just through their high potential returns, but also their short payback periods. A short payback period signifies that farmers can recover their initial investment within a single harvest season. This aspect, combined with the high returns on investment (NPV and IRR) discussed earlier, presents a powerful incentive for wider adoption, particularly among resource-constrained smallholder farmers.

A short payback period translates to reduced financial risk for farmers adopting these innovations (Akinyi et al., 2022). Knowing they can recoup their investment quickly can incentivize them to experiment with these practices and potentially see the benefits firsthand. This can lead to a snowball effect, where initial success stories encourage other farmers to adopt the innovations, accelerating the diffusion of these technologies. Furthermore, the

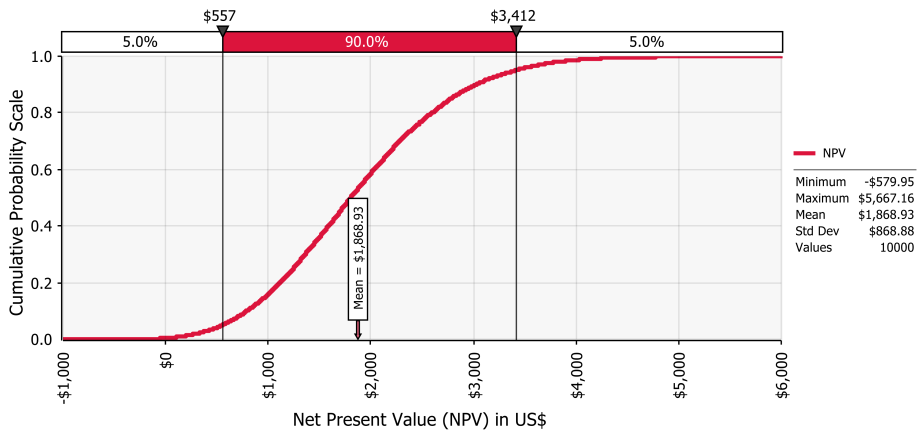

FIGURE 4
The cumulative probability distribution of Net Present Value (US$/ha) for "Certified seeds" innovation in Ethiopia.

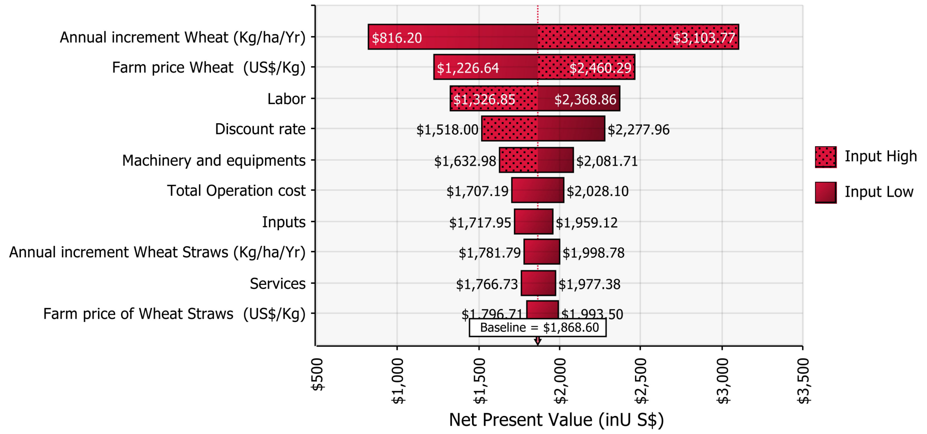

FIGURE 5
Inputs ranked by effect on the mean Net Present Value for "certified seeds" innovation in Ethiopia.

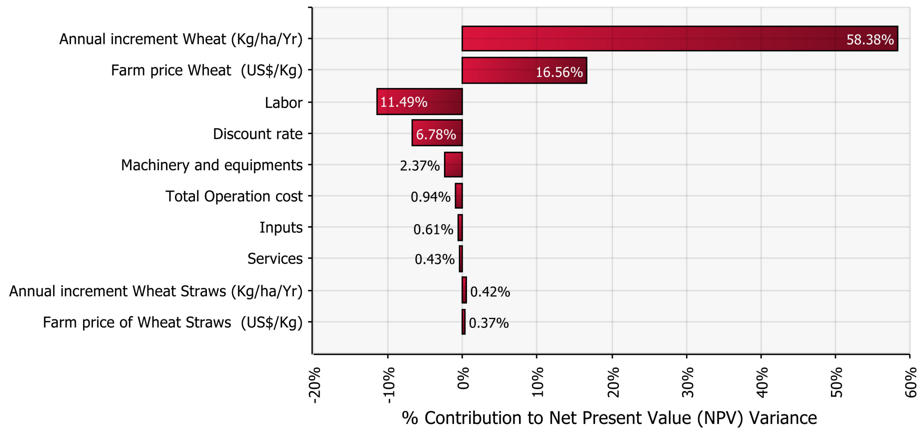

FIGURE 6
Percentage contribution to variation in Net Present Value for "Certified seeds" innovation in Ethiopia.

positive cash flow generated within a year can improve household food security and empower farmers to invest in other farm improvements, creating a cycle of continuous progress.

The optimal choice for individual farmers will still depend on factors like risk tolerance, crop type, and market conditions. This highlights the need for targeted extension services. Extension efforts should emphasize the rapid return on investment associated with these innovations and tailor recommendations based on individual circumstances. Financial inclusion initiatives like micro-loans or input credit programs specifically designed with the payback periods in mind can make these innovations more accessible to smallholder farmers.

By focusing on the combined strengths of short payback periods, high potential returns, and targeted support mechanisms, policymakers can create a compelling case for wider adoption and attracting private sector investments and impact investors. This can unlock the transformative potential of these agricultural innovations for boosting productivity, improving livelihoods, and fostering inclusive growth in rural communities.

While the economic benefits are promising, long-term sustainability and synergies of combining several practices requires further investigation. The potential impact of these practices on soil health and environmental factors needs to be assessed. Research by Abhijeet et al. (2023) emphasizes the importance of integrating sustainability considerations into agricultural development strategies. The successful adoption and diffusion of these innovations relies heavily on effective knowledge dissemination and capacity building for farmers. Collaboration with extension services, farmer associations and multi-stakeholder platforms is crucial to ensure farmers understand the benefits, implementation requirements, and potential risks associated with each innovation.

Despite the high potential returns on investment evidenced by the IRR, a crucial question arises: why are these innovations not being adopted at scale by farmers? Research suggests several reasons for this paradox. Limited access to information and knowledge about the innovations, coupled with risk aversion among farmers, can be significant barriers. Additionally, even with high potential returns, upfront costs (i.e., US$ 329, US$325 and US$322 per hectare for "Optimal fertilizer", "certified seeds" and drainage innovations respectively; Supplementary Tables A1–A3) and lack of access to credit, particularly for smallholder farmers, can hinder adoption.

Another key factor hindering wider adoption is the unavailability of quality seeds at the right place and time (Abebaw et al., 2023). Insufficient certified seed production and distribution networks can leave farmers without access to these improved varieties when they need them most for planting (Beshir, 2013). This is compounded by a poor promotion system. Limited awareness about the benefits of certified seeds and inadequate information on their proper use can leave farmers hesitant to adopt them.

This situation highlights the need for a two-pronged approach. Firstly, investing in the seed production and distribution system is crucial to ensure a reliable supply of certified seeds throughout the planting season and across all regions. Secondly, strengthening seed promotion efforts through extension services and farmer training programs can raise awareness about the advantages of certified seeds and equip farmers with the knowledge required to utilize them effectively. By addressing these challenges, policymakers can bridge the gap between the potential and reality of certified seed adoption, unlocking their power to contribute to agricultural productivity and food security in Ethiopia.

To bridge this gap and ensure the scaling up of these practices, several policies and institutional responses are necessary. Governments, policymakers and private sector stakeholders can play a critical role by:

- Strengthening extension services: Investing in extension services to bridge the knowledge gap and provide farmers with training and information on these innovations.
- Facilitating access to credit: Developing financial inclusion initiatives such as micro-credit programs or loan guarantees to help farmers overcome upfront costs.
- Risk mitigation strategies to de-risk food systems: Exploring crop insurance schemes or other risk mitigation strategies to incentivize adoption, particularly for risk-averse farmers.
- Market access and infrastructure development: Improving market access for farmers to ensure they can reap the benefits of increased production through better prices.

The sensitivity findings underscore the critical role of yield fluctuations and market conditions in determining the financial success of these agronomic practices. A study by Feuerbacher et al. (2018) recognized a discernible correlation between socio-economic status and the accessibility of markets, underscoring the importance of affordability in agricultural practices and ease of sale.

5 Conclusion

This study underscores the significant economic viability of three agroecological innovations—optimal fertilizer rate, certified seed, and drainage improvements—within the Lemo, Munesa, and Goba districts of Ethiopia. The substantial yield increases observed from these innovations can significantly enhance household food security and contribute to lower food prices, aligning with the principles of sustainable growth.

The 22% yield increase from optimal fertilizer rates and the high return on investment (exceeding 100% IRR) for certified seeds and fertilizers highlight their economic benefits. The short payback periods associated with these innovations reduce financial risks and provide strong incentives for adoption among smallholder farmers. These innovations not only boost productivity and income but also create employment opportunities, thereby fostering rural economic growth.

Equitable access to these innovations is essential, particularly for women farmers who face significant barriers in accessing resources and training. Empowering women through targeted training and access to credit can enhance agricultural productivity and contribute to community well-being. The adoption of these innovation among the youth and women can be boosted through strengthened extension services, improved seed production and distribution, financial inclusion initiatives. By implementing these measures, policymakers and stakeholders can unlock the transformative potential of agroecological innovations, driving productivity, improving livelihoods, and fostering inclusive growth in Ethiopia's rural. In the future, further research on the long-term sustainability and environmental impact of these practices is necessary to ensure their sustainable adoption and scaling up.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Internation Center for Tropical Research (CIAT) Institutional Review Board (IRB). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SN: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SO: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. DT: Data curation, Investigation, Writing – review & editing. DA: Writing – original draft. JM: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The Agroecological Transitions for Building Resilient and Inclusive Agricultural and Food Systems (TRANSITIONS) programme is funded by the European Commission through its DeSIRA initiative and managed by the International Fund for Agricultural Development (IFAD). This publication was produced by the "Private Sector Incentives and Investments (PSII) for Climate Change, Resilience and Environmental Sustainability" project under the European Commission - IFAD Grant Number: 2000003771 and CGIAR initiative on Transformative Agroecology.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2024.1502786/full#supplementary-material

References

Abebaw, Y., Wubetu, A., and Marelign, A. (2023). Enhancing access and adoption of improved seed for food security of Ethiopia (A review). *Develop. Country Stud.* 13. doi: 10.7176/dcs/13-3-02

Abhijeet, , Sahu, K. K., Bardhan, R., Chouhan, N. S., Dixit, D., Tripathi, S., et al. (2023). A comprehensive review on role of agricultural extension services in the sustainable development of global agriculture. *Int. J. Environ. Climate Change* 13, 3514–3525. doi: 10.9734/IJECC/2023/V13I103021

Addise, T., Bedadi, B., Regassa, A., Wogi, L., and Feyissa, S. (2022). Spatial variability of soil organic carbon stock in Gurje Subwatershed, Hadiya Zone, Southern Ethiopia. *Appl. Environ. Soil Sci.* 2022, 1–12. doi: 10.1155/2022/5274482

Adunea, D., and Fekadu, B. (2019). Adoption determinants of row planting for wheat production in Munesa District of Oromia Region, Ethiopia. *J. Agric. Extension Rural Dev.* 11 (2), 25–34. doi: 10.5897/jaerd2018.0993

Akinyi, D. P., Ng'ang'a, S. K., Ngigi, M., Mathenge, M., and Girvetz, E. (2022). Cost-benefit analysis of prioritized climate-smart agricultural practices among smallholder farmers: evidence from selected value chains across sub-Saharan Africa. *Heliyon* 8 (4), 1–11. doi: 10.1016/J.HELIYON.2022.E09228

Ali, A., Rahut, D. B., Behera, B., and Imtiaz, M. (2015). Farmers' Access to certified wheat seed and its effect on poverty reduction in Pakistan. *J. Crop Improve.* 29. doi: 10.1080/15427528.2015.1004147

Anteneh, A., and Asrat, D. (2020). "Wheat production and marketing in Ethiopia: Review study," in *Cogent Food and Agriculture*, vol. 6 (1), pp. 1–14. doi: 10.1080/23311932.2020.1778893

Assefa, A., Belay, S., and Kloos, H. (2024). Evaluation of *in-vitro* antibacterial activity of extracts of Calpurina aurea, Vernonia amygdalina and Rumex Nepalensis in Goba district, southeastern Ethiopia. *Egypt. J. Basic Appl. Sci.* 11 (1), 69–83. doi: 10.1080/2314808X.2024.2312785

Awulachew, S. B. (2006). "Improved agricultural water management: Assessment of constraints and opportunities for agricultural development in Ethiopia," in *Proceeding of a MoARD/MoWR/IMWI Symposium and Exhibition*. Eds. S. B. Y. Awulachew, M. Menker, D. Abesha, T. Atnafe and Wondimmkun, (Addis Ababa, Ethiopia), 23–24.

Ayalew, H., Chamberlin, J., and Newman, C. (2022). Site-specific agronomic information and technology adoption: A field experiment from Ethiopia. *J. Dev. Econ.* 156, 1–22. doi: 10.1016/j.jdeveco.2021.102788

Baglan, M., Mwalupaso, G. E., Zhou, X., and Geng, X. (2020). Towards cleaner production: Certified seed adoption and its effect on technical effciency. *Sustain. (Switzerland)* 12 (4), 1–17. doi: 10.3390/su12041344

Belete, Y., Shimelis, H., and Laing, M. (2022). Wheat production in drought-prone agro-ecologies in Ethiopia: diagnostic assessment of farmers' Practices and sustainable coping mechanisms and the role of improved cultivars. *Sustain. (Switzerland)* 14 (13), 1–10. doi: 10.3390/su14137579

Beshir, A. B. (2013). *Access to Seed and Variety Adoption of Farmers in ETHIOPIA: A Case of Open Pollinated Maize in Drought-Prone Central Rift Valley.* Nagoya University.

Caplan, D., Dixon, M., and Zheng, Y. (2017). Optimal rate of organic fertilizer during the flowering stage for cannabis grown in two coir-based substrates. *HortScience* 52 (12), 1796–1803. doi: 10.21273/HORTSCI12401-17

Corner-Dolloff, C., Loboguerrero, A. M., Lizarazo, M., Nowak, A. C., Howland, F., Andrieu, N., et al. (2014). *Climate-smart agriculture investment prioritization framework* (Colombia: CIAT, Cali).

Desta, B. T., Gezahegn, A. M., and Tesema, S. E. (2021). Impacts of tillage practice on the productivity of durum wheat in Ethiopia. *Cogent Food Agric.* 7 (1), 1. doi: 10.1080/23311932.2020.1869382

Dhiman, J. S., Kang, M. S., Parshad, V. R., Khanna, P. K., Bal, S. S., and Gosal, S. S. (2010). Improved seeds and green revolution. *J. New Seeds* 11 (2), 65–103. doi: 10.1080/1522886X.2010.481777

Elias, A., Nohmi, M., and Yasunobu, K. (2017). Cost-benefit analysis of cultivating three major crops and its implication to agricultural extension service: A case study in North-West Ethiopia. *Japan. J. Agric. Econ.* 19 (0), 31–36. doi: 10.18480/jjae.19.0_31

Ewert, F., Baatz, R., and Finger, R. (2023). Agroecology for a sustainable agriculture and food system: from local solutions to large-scale adoption. *Annu. Rev. Res. Econ.* 15, 351–381. doi: 10.1146/annurev-resource-102422-090105

Fan, S., Headey, D., Rue, C., and Thomas, T. (2021). Food systems for human and planetary health: Economic perspectives and challenges. *Annu. Rev. Res. Econ.* 13, 131–156. doi: 10.1146/annurev-resource-101520-081337

FAO, IFAD, UNICEF, WFP and WHO (2022). *The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable.* Rome, FAO. Available online at: https://doi.org/10.4060/cc0639en.

FAO (2010). *Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation* (Rome, Italy: Food and Agriculture Organization (FAO)).

Farrow, S., and von Winterfeldt, D. (2020). Retrospective benefit–cost analysis of security-enhancing and cost-saving technologies. *J. Benefit-Cost Anal.* 11 (3), 479–500. doi: 10.1017/bca.2020.24

Feuerbacher, A., Luckmann, J., Boysen, O., Zikeli, S., and Grethe, H. (2018). Is Bhutan destined for 100% organic? Assessing the economy-wide effects of a large-scale conversion policy. *PloS One* 13 (6), 1–24. doi: 10.1371/journal.pone.0199025

Harris, R. H., Armstrong, R. D., Wallace, A. J., and Belyaeva, O. N. (2016). Effect of nitrogen fertiliser management on soil mineral nitrogen, nitrous oxide losses, yield and nitrogen uptake of wheat growing in waterlogging-prone soils of south-eastern Australia. *Soil Res.* 54 (5), 619–633. doi: 10.1071/SR15292

Hartman, J. C., and Schafrick, I. C. (2004). The relevant internal rate of return. *Eng. Economist*, 139–158. doi: 10.1080/00137910490453419

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Bodirsky, B. L., Pradhan, P., et al. (2021). Articulating the effect of food systems innovation on the sustainable development goals. *In Lancet Planetary Health* 5 (1), 266–272. doi: 10.1016/S2542-5196(20)30277-1

Howarth, R. B. (2009). Discounting, uncertainty, and revealed time preference. *Land Economics*, 24–40. doi: 10.3368/le.85.1.24

Iizumi, T., Iseki, K., Ikazaki, K., Sakai, T., Shiogama, H., Imada, Y., et al. (2024). Increasing heavy rainfall events and associated excessive soil water threaten a protein-source legume in dry environments of West Africa. *Agric. For. Meteorol.* 344, 2–10. doi: 10.1016/j.agrformet.2023.109783

Jayne, T. S., and Sanchez, P. A. (2021). Agricultural productivity must improve in sub-Saharan Africa. *Science* 372, 6546. doi: 10.1126/science.abf5413

Jones, S. K., Bergamini, N., Beggi, F., Lesueur, D., Vinceti, B., Bailey, A., et al. (2022). Research strategies to catalyze agroecological transitions in low- and middle-income countries. *Sustain. Sci.* 17 (6), 2557–2577. doi: 10.1007/s11625-022-01163-6

Khatri-Chhetri, A., Aggarwal, P. K., Joshi, P. K., and Vyas, S. (2017). Farmers' prioritization of climate-smart agriculture (CSA) technologies. *Agric. Syst.* 151. doi: 10.1016/j.agsy.2016.10.005

Legesse, G., Hayicho, H., and Alemu, M. (2019). Assessment of the trend, cause and effect of deforestation using GIS and remote sensing in Goba District, Bale Zone, South Eastern Ethiopia. *Agric. Sci.* 10 (04), 546–566. doi: 10.4236/as.2019.104044

Lizarazo, M., Sandoval, D., Eitzinger, A., and Lopera, D. (2021). *Climate-smart agriculture prioritization framework (CSA-PF) report for guyana*.

Mesfin, S., Haile, M., Gebresamuel, G., Zenebe, A., and Gebre, A. (2021). Establishment and validation of site specific fertilizer recommendation for increased barley (Hordeum spp.) yield, northern Ethiopia. *Heliyon* 7 (8), 1–10. doi: 10.1016/j.heliyon.2021.e07758

Mockshell, J., and Kamanda, J. (2018). Beyond the agroecological and sustainable agricultural intensification debate: Is blended sustainability the way forward? *Int. J. Agric. Sustainability* 16 (2), 1–23. doi: 10.1080/14735903.2018.1448047

Mockshell, J., and Nielsen Ritter, T. (2024). Applying the six-dimensional food security framework to examine a fresh fruit and vegetable program implemented by self-help groups during the COVID-19 lockdown in india. *World Dev.* 175, 1–13. doi: 10.1016/j.worlddev.2023.106486

Mogaka, B. O., Ng'ang'a, S. K., and Bett, H. K. (2022). Comparative profitability and relative risk of adopting climate-smart soil practices among farmers. a cost-benefit analysis of six agricultural practices. *Climate Serv.* 26, 1–11. doi: 10.1016/J.CLISER.2022.100287

Motarjemi, S. K., Styczen, M. E., Petersen, R. J., Jensen, K. J. S., and Plauborg, F. (2023). Effects of different drainage conditions on nitrogen losses of an agricultural sandy loam soil. *J. Environ. Manage.* 325. doi: 10.1016/j.jenvman.2022.116267

Mwongera, C., Nowak, A., Notenbaert, A. M. O., Grey, S., Osiemi, J., Kinyua, I., et al. (2018). "Climate-smart agricultural value chains: Risks and perspectives," in *The climate-smart agriculture papers*. Eds. T. Rosenstock, A. Nowak and E. Girvetz (Cham: Springer), 235–245.

Negra, C., Remans, R., Attwood, S., Jones, S., Werneck, F., and Smith, A. (2020). Sustainable agri-food investments require multi-sector co-development of decision tools. *Ecol. Indic.* 110, 1–8. doi: 10.1016/j.ecolind.2019.105851

Ng'ang'a, S. K., Miller, V., and Girvetz, E. (2021). Is investment in Climate-Smart-agricultural practices the option for the future? Cost and benefit analysis evidence from Ghana. *Heliyon* 7, 14. doi: 10.1016/J.HELIYON.2021.E06653

Nigus, M., Shimelis, H., Mathew, I. K., and Abady, S. (2022). Wheat production in the highlands of Eastern Ethiopia: opportunities, challenges and coping strategies of rust diseases. *Acta Agricult. Scandinavica Sect. B: Soil Plant Sci.* 72 (1), 563–575. doi: 10.1080/09064710.2021.2022186

Noori, M., Miller, R., Kirchain, R., and Gregory, J. (2018). How much should be invested in hazard mitigation? Development of a streamlined hazard mitigation cost assessment framework. *Int. J. Disaster Risk Reduct.* 578–584. doi: 10.1016/j.ijdrr.2018.01.007

Pais, I. P., Moreira, R., Semedo, J. N., Ramalho, J. C., Lidon, F. C., Coutinho, J., et al. (2023). Wheat crop under waterlogging: potential soil and plant effects. *Plants.* 12 (1). doi: 10.3390/plants12010149

Palisade Corporation (2010). *Risk Analysis and Simulation Add-In for Microsoft Excel or Lotus 1-2-3.* Release 6.1 User Guide. (Newfield, NY: Palisade Corporation).

Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., et al. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nat. Sustain.* 3 (10), 809–820. doi: 10.1038/s41893-020-00617-y

Rios, A. R., Shivley, G. E., and Masters, W. A. (2009). *Farm productivity and household market participation: evidence from LSMS data*. International Association of Agricultural Economists (IAAE), 1–42. doi: 10.22004/ag.econ.51031

Schmidt, E., and Tadesse, F. (2019). The impact of sustainable land management on household crop production in the Blue Nile Basin, Ethiopia. *Land Degradation Dev.* 30 (7), 777. doi: 10.1002/ldr.3266

Sedebo, D. A., Li, G. C., Abebe, K. A., Etea, B. G., Ahiakpa, J. K., Ouattara, N., et al. (2021). Smallholder farmers' climate change adaptation practices contribute to crop production efficiency in southern Ethiopia. *Agron. J.* 113 (6), 4627–4638. doi: 10.1002/agj2.20900

SenseIt (2017). *TreePlan Decision Tree Excel Add-in*. TreePlan Software Sense Guide. Available online at: https://treeplan.com/ (Accessed June 13, 2024).

Smil, V. (2004). Improving efficiency and reducing waste in our food system. *Environ. Sci.* 1 (1), 17–26. doi: 10.1076/evms.1.1.17.23766

Tadesse, G., Zavaleta, E., Shennan, C., and FitzSimmons, M. (2014). Prospects for forest-based ecosystem services in forest-coffee mosaics as forest loss continues in southwestern ethiopia. *Appl. Geogr.* 50, 144–151. doi: 10.1016/j.apgeog.2014.03.004

Tanto, T., and Laekemariam, F. (2019). Impacts of soil and water conservation practices on soil property and wheat productivity in Southern Ethiopia. *Environ. Syst. Res.* 8 (1), 1–9. doi: 10.1186/s40068-019-0142-4

Thornton, P. K., Schuetz, T., Förch, W., Cramer, L., Abreu, D., Vermeulen, S., et al. (2017). Responding to global change: A theory of change approach to making agricultural research for development outcome-based. *Agric. Syst.* 152, 145–153. doi: 10.1016/j.agsy.2017.01.005

Thrift, S. M., and von Winterfeldt, D. (2021). Risk-informed benefit–cost analysis for homeland security R&D: methodology and an application to evaluating the advanced personal protection system for wildland firefighters. *J. Benefit-Cost Anal.* 12, 335–366. doi: 10.1017/BCA.2020.33

Wang, Y., Yuan, Y., Yuan, F., Ata-UI-Karim, S. T., Liu, X., Tian, Y., et al. (2023). Evaluation of variable application rate of fertilizers based on site-specific management zones for winter wheat in small-scale farming. *Agronomy* 13 (11), 1–19. doi: 10.3390/agronomy13112812

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., and Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agron. Sustain. Dev.* 40 (6), 1–13. doi: 10.1007/s13593-020-00646-z

Williams, E. M., Väisänen, H., and Padmadas, S. S. (2022). Women's economic empowerment in sub-Saharan Africa: Evidence from cross-national population data. *Demogr. Res.* 47, 416–450. doi: 10.4054/DEMRES.2022.47.15

World Bank (2009). Awakening Africa's Sleeping Giant Prospects for Commercial Agriculture in. In *Library of Congress*. World Bank. Available online at: http://hdl.handle.net/10986/2640.